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The blade of the future: wind turbine blades in 2040

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Management Summary

Expecting a 27MW Horizontal-Axis Wind Turbines (HAWT) platform to be the norm for wind turbines in 2040, the blades will have to be around 145m long. This will require a robust blade design, taking into account all inherent uncertainties of the design, production, testing, and operation to accurately predict lifetime and obtain reliable maintenance intervals. The slenderness of very long blades will require a more aero-elastically tailored design. Moreover, we expect the design will aim for segmented blades, not only to facilitate transportation, but also to reduce handling and installation loads on the blade itself and the installation equipment.

The blade of the future will be further optimised using an integral approach combining the aeroelastic and structural behaviour requirements with considerations such as life time, robustness and surface degradation. This integral optimisation will entail the entire blade design, including segmentation locations and joining techniques. Optimal locations for integrated sensors for structural health monitoring are also determined. This introduces opportunities for a free-form design optimization procedure such as topology optimisation used to design the shear load bearing structure of the blade.

Some of the optimisation in design can only be achieved by more automated manufacturing. Increasing repetitive quality, 24 hours per day in some part of the production line will reduce room for error and aid manual labour. Sections of the blade that are prone to waviness or wrinkles, like the root, could be produced with automated tape laying and/or production on a positive mould. A topology optimized core of the blade leading to a shear structure rather than shear webs will be achieved with continuous fibre reinforced 3D thermoplastic printing. Finishing of a mass-produced segmented 145m blade will be done in an automated way.

In order to really accelerate the design and certification process of wind turbine blades, reduce development cost, and make the design of blades of the future possible, virtual testing will be required, thus omitting a full scale physical test of a prototype blade. The accuracy of the numerical model can be assessed by including all uncertainties in the numerical model and in the experimental results. As the available computing power keeps growing, competition will push companies to rely more on computer simulations to increase economic efficiency and deliver more robust products. Standardized validation methodologies will be necessary for objectively quantifying the predictive capabilities of numerical simulation models. With certification bodies adopting these methodologies, validated simulations will be used to certify the blade of the future.

Using embedded sensors, the blade of the future will be monitored continuously to ensure optimal operation and maintenance. Using actual local weather forecast and market information, digital twin technology will enable the prediction of the future state of the blade. These more automated control systems will be combined with damage growth monitoring, allowing optimization for preventive repairs, while minimizing down time of the turbine.

Focus in the design phase is needed to facilitate ease of dismantling at end-of-life and to get fully reusable materials introduced in the wind turbine structure. Polymers build with re-mouldable or reversible chemistry are expected to take over the rigid thermoset formulation currently used. Especially those based on liquid crystal polymers will have become a game changer by 2040.

Contents

1 Introduction

The drive for lower levelized costs of energy for wind turbines has also led to larger and larger wind turbines, often limited only by the site conditions, permitting criteria and environmental impact assessment. Harnessing wind power offshore competitively, requires not only a scale increase in size, but also an efficiency gain in the supply chain. This leads to a cost cutting spiral that reduces margins throughout the development chain. Increased installed capacity and a larger share of the offshore wind energy in the mix already shows a focal shift from “lowering Levelised Cost of wind Energy (LCoE) only” to “how can we maximize the value of the produced wind power?”. This once again has effect on the size of the turbines, and especially the blades as the cut-in wind speed needs to reduce to be able to deliver power over a larger range of wind speeds. The result is a relatively low rotor power density [W/m2] rating for large turbines combined with an ever growing rated power. Blades are expected to grow in access of 118m by 2024. These blade lengths were never deemed possible in the first decade of this century. To get the most out of a certified blade design, OEMs often boost their turbine platforms, leading to higher rotor power densities, while reducing capacity factors. Examples are the V164 of Vestas (8 -> 9.5MW, 80m blades) and the Haliade X of GE Offshore Energy (12 -> 14MW, 107m blades). There is enough reason to assume that the announced turbines of Siemens Gamesa (SG14-222, 108m blades), Vestas (V236-15.0, 115.5m blades) and MingYang (MySE 16.0 – 242, 118m blades) will follow that same strategy.

Assuming steady growth, what will be limiting factors? Maximum blade length is most probably not dictated by material limitations, but rather by ability to handle the product. A segmented blade could overcome these limitations, but requires additional installation steps and comes at a design/weight penalty. Perhaps the hub height and tower diameter could be a limiting consideration as well. The effect of the aerodynamic pressure of a very large rotor at a relatively large distance from the fixed foundation (or floating foundation!) can become too large to overcome. Combine this with an increased nacelle weight and we may very well see turbine growth being limited by steel prices rather than physical boundaries. The often cited “square cube law” in combination with high commodity prices can be another limiting factor.

But for now, let’s assume turbine growth will develop along today’s trendline for the coming years. We then expect to see rated powers of ~20MW by 2030 and ~27MW by 2040, see Figure 1-1.

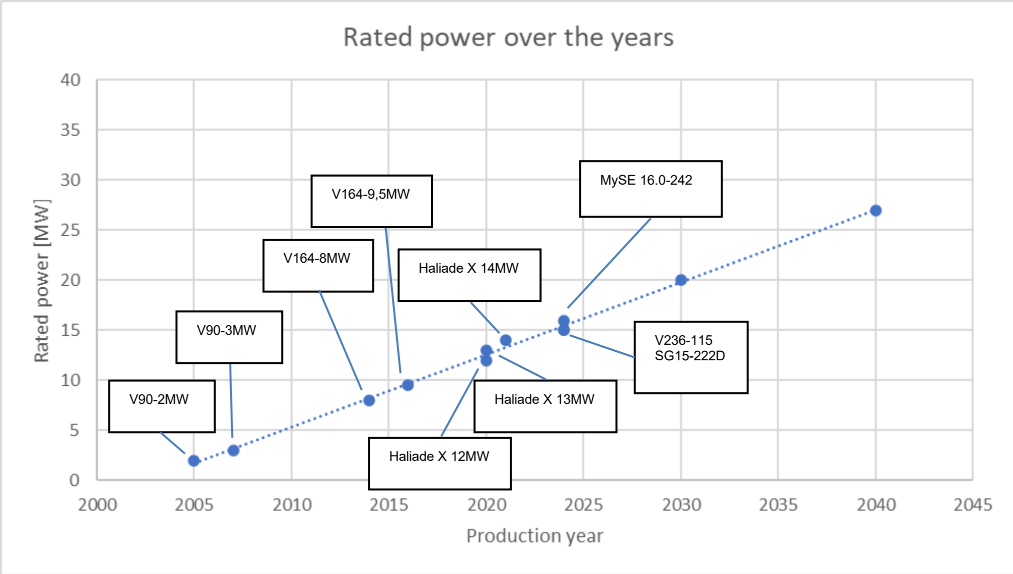

Figure 1-1. Development of rated power over the last 15 years, extrapolated to 2040

A 27MW wind turbine corresponds to blade lengths in the order of 145m, see Figure 1-2. The question is whether the business case for those turbine sizes still holds and whether the classical blade designs and production processes currently used can realise those massive blades of the future.

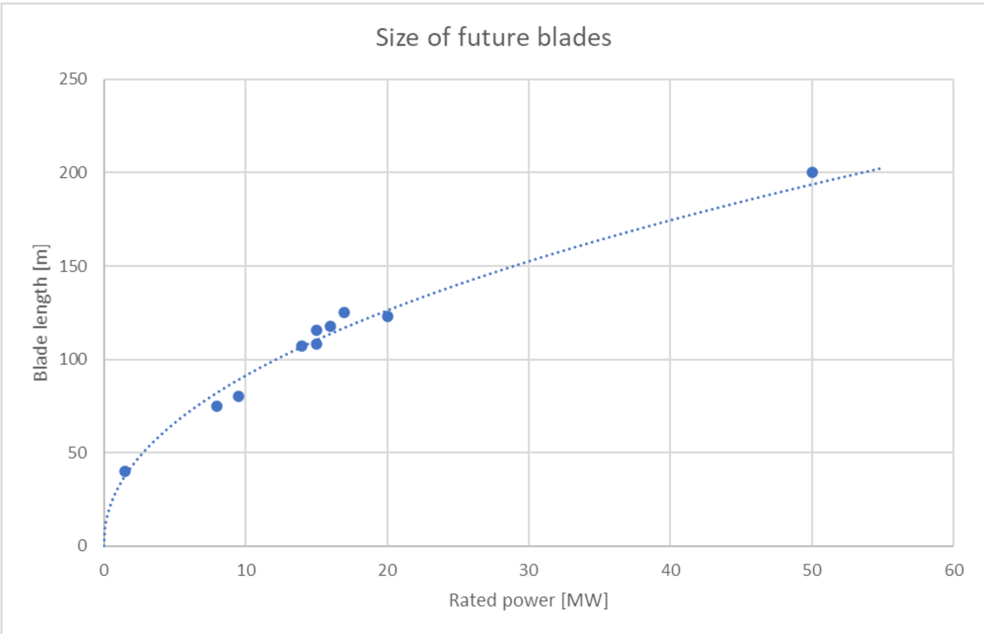

Figure 1-2. Blade length as a function of rated power (estimated), plotting for the turbines mentioned in this chapter and Figure 1-1

A reliable product depends on the robustness of its design. This also holds for wind turbine blades of 145m. To be able to design robustly, one needs to factor in all aspects of the blade, from design to production to testing and operation. Robustness comes at a cost, but will pay off in the long run. On the other hand,

project developers are looking for favourable financing in the early stages of a project, often having CAPEX as a strong driver. When optimizing a blade for robustness, this balance between operational reliability (OPEX) and initial cost competitiveness (CAPEX) proves very important. Stakeholders in this decision process are blade manufacturers, turbine OEMs/O&M companies as well as wind farm owners/developers.
Moving from a interface-based design to an integrated design approach offers optimization opportunities. However, a true integrated design requires a digital transition first. The system approach towards designing a turbine has large effects on the blade design and vice versa. Having an in-depth understanding of all uncertainties in material properties, manufacturing, machining and finishing gives another opportunity: we can move away from physically testing these huge blades and certify a blade series as long as they stay within the given bandwidth of production parameters with their corresponding statistical aspects. Simplified FEA models as well as fast analysis of complex FEA models will aid this development.

Reducing uncertainty in production provides opportunities to optimize other aspects of a blade design. Automation is one way to create repeatable quality over a very large batch of products, continuously. Automating part of the production of blades also opens the way to selecting other design methods, such as topology optimisation. One could think of a whole array of different production methods that will be available in 2040. From 3D printing of continuous fibre composites, to automated kitting, from automated kit placement to automated blade handling and finishing. Other parts of the production process are best left to manual labour, as flexibility and problem solving capabilities of humans are hard to compete with.

Lastly the environmental impact of blades will not be a discussion point anymore by 2040. We will have moved away from traditional fibre reinforced epoxy/polyester with balsa (or other non-recyclable sandwich materials) to bio-based or other recyclable materials that will allow a blade to be fully recyclable and produce zero-waste [1].

Assuming the basic lay out of the blade to stay the same and assuming a steady growth of rated capacity of HAWTs, this study looks at how a 145m blade will be designed, produced, tested and operated. Since the blade is part of a complex life-cycle, the entire life-cycle of the blade will be considered and improvements will be proposed for various stages of the life-cycle. In Figure 1-3, a flow diagram, representing the life-cycle of a wind turbine blade, is shown. In this figure, proposed improvements for various stages of the life-cycle are presented, highlighting the stages of the life-cycle affected by the work proposed in this document.

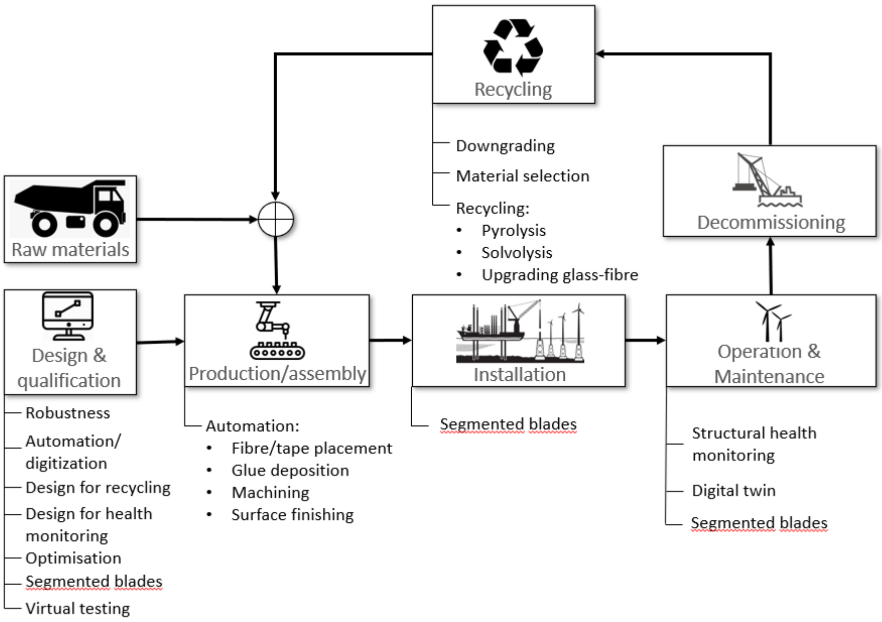

Figure 1-3 Wind turbine blade life-cycle

We will look at the aforementioned design aspects in Chapter 2, opportunities for automation in the production process will be explored in Chapter 3. Chapter 4 will deal with the developments in testing, followed by considerations around operation and maintenance aspects of the blade of the future, in Chapter 5. Environmental aspects including recycling will be covered in Chapter 6. Finally, Chapter 7 will outline the blade of the future as we envision it for 2040.

2 Design

2.1 Blade design considerations

As discussed in the introduction, there is a trend towards longer blades for both onshore as well as offshore wind turbines. However, there are several limiting factors in increasing the blade length. Besides the limiting factor of the hub height and the corresponding loads at the base of the wind turbine that was mentioned, another limiting factor is the choice of material. An increased use of carbon fibre is anticipated for longer blades, which raises new questions regarding robustness, recyclability and waste management. Furthermore, the aeroelastic response, design optimisation, the effect of surface degradation, and segmented blades will play a major role and will briefly be presented in this section. Recyclability will be discussed in more detail in Chapter 6.

Robustness
The complexity of wind turbine blade designs combined with complex production and assembly methods results in uncertainties in the performance of manufactured parts compared to their design specifications. In order to extend the limits of current blade design, a focus on robust design will be necessary to ensure that these inherent uncertainties do not result in an unacceptable risk of possible failure and accompanied maintenance. Robust design will be addressed in more detail in Section 2.2.

Aeroelastic response
With ever increasing blade lengths, the aeroelastic behaviour of the wings not only becomes increasingly important, but also offers opportunities for further optimisation of the blade design. By exploiting the inherent coupling between bending and twisting of the wind turbine blade, the aeroelastic deformations of the blade can be tailored such that it results in favourable aerodynamic and structural performance. This is called aeroelastic tailoring and can broadly be induced in two ways: through geometry (e.g. curved or swept blades) or through the anisotropic properties of composite materials (i.e. extension-shear or bend-twist behaviour induced by off-axis plies). Aeroelastic tailoring will be addressed in more detail in Section 2.3.

Design optimisation
In designing the blade of the future, design optimisation will provide further opportunities to extend the current limits of blade design and improve the efficiency of blades, thereby reducing the overall LCoE. These opportunities will be presented in more detail in Section 2.3.

Surface degradation
During their lifetime, wind turbine blades suffer from surface degradation due to the accumulation of dirt on the surface, erosion, and other damage to the coating, as illustrated in Figure 2-1. The increased roughness of the blades causes a significant decrease in energy production by reducing the maximum lift and by introducing drag. Blades that have been operating for as little as two years have already been affected by energy loss leading to additional maintenance because of surface degradation.

Figure 2-1: Blade surface and leading edge degradation due to pitting and erosion [2]

Several tapes,coatings and shells have been developed to protect the turbine blade surface and leading edge from minor impacts and erosion. Nevertheless, degradation of the blade surface cannot be prevented entirely, and maintenance is undesirable due to high costs, especially for offshore turbines.

Segmented blades
Additional limiting factors for blade length are related to transportation, manufacturing and installation. Although transportation over water is less restricted than transportation over land, longer blades for offshore wind farms are still challenging to get to their installation location. Longer blades also require larger facilities for manufacturing. Not only does the production plant need to be longer to fit the longer blades, it also needs to be higher in order to close the mould and subsequently lift the blade from the mould after post-cure. These large production facilities require large investments and the necessity for extension for the future generation of even larger blades. Finally, in longer blades the loads during handling, transport, and installation may become dominant over the operational loads, resulting in heavier blade designs, which in turn reduce the turbine’s efficiency.

These challenges and drawbacks in increasing blade length have inspired the introduction of segmented wind turbine blades. This idea is no longer only suggested in academic literature, but has also been implemented by GE Onshore [3].

Figure 2-2: Prototypes of segmented blades using T-bolt joints [4]

Several considerations play a part in the design of segmented turbine blades, their location for segmentation, and their joining technique. The following (cost) considerations play a role for the design of segmented blades (based on Peeters et al. [4]):

- Initial capital costs:
  - **Manufacturing costs:** manufacturing of longer blades requires larger production facilities than segmented blades. However, segmented blades require the design and production of a joint, which is more complex. Furthermore, assembly of the blade is an extra production step that has to be done either in the facility or onsite. Segmented blade may need additional production moulds.
  - **Tolerance requirements:** Depending on the joint used in the segmented blade, the tolerances required in the production may be stricter.
  - **Production complexity and accuracy:** Although lighter joints may be beneficial, they can be more complex to produce. The loads as well as the complexity of the joint also depend highly on the location of the segmentation.
  - **Ability to use conventional production methods:** Choosing production methods and joint technologies that are already used in wind turbines has many benefits. Firstly, current manufacturing plants will already have the required production facilities. Secondly, certification of known technologies is faster and cheaper than certification of new techniques.
  - **Quality control**: On the one hand quality control of a segmented blade facilitates segmented quality assurance and segmented testing of the blades. On the other hand, the joint itself also needs quality control and testing.
  - **Positioning accuracy and speed of assembly:** If the assembly is done onsite or even when the inboard section is already connected to the hub, transporting the blade in segments enables the transport of multiple blades on a ship. Furthermore, lifting smaller and lighter segments can broaden the weather window in which a crane can operate. Moreover, the blade experiences lower loads during handling if it is manufactured, transported, and installed in segments. This means that these loads will not be dominant over the operational loads, and lighter designs are possible, potentially favouring energy production. On the other hand, assembly onsite could increase the complexity of and time required for installation. Furthermore, connecting the segments when the inboard section is already connected to the hub requires different concepts and tools.

- Annual energy production:
  - **Reliability:** Damages to the wind turbine blade cause downtime of the turbine, which reduces annual energy production. A segmented blade, therefore, needs to be at least equally reliable to minimize downtime. This includes reducing the need for maintenance by means of a joint design that is robust to variations in the material properties and the production process, as well as structural health monitoring of the blade for early detection of problems.
  - **Aerodynamics**: The aerodynamics of the blade determine the energy production of the turbine. Therefore, the aerodynamics (i.e. smoothness, seam dimensions, susceptibility to erosion) play a large role in the decision on where and how the blade should be segmented.
  - **Weight of the joint:** A heavy joint increases the weight of the blade and the loads on the blade. The weight of the joint is strongly dependent on the location of the joint and selected joining method.

- Annual operational expenses:
  - **Requiring minimal inspection:** Inspection of wind turbine blades, especially in offshore wind parks, is expensive and should be minimized. A robust design and structural health monitoring minimize the need for inspection.
  - **Ease of repair during service:** A benefit of segmented blades is that it allows for replacement of only the outboard section in case of, for example, lightning strike.
  - **Possibility for replacing segments**: As outboard segments can be replaced without changing the root section, the same root section can be used for different blades. This also provides possibilities to design different segments for different lifetimes, for example, 50 years for the root section and 25 years for the outboard section.

The decision on whether or not a blade should be segmented, and if so, what should be the location of segmentation and which joint should be used to assemble the segments is a complex optimisation problem that depends on all aforementioned aspects.

2.2 Robustness & digitisation

The complexity of wind turbine blade designs combined with their corresponding production and assembly methods, result in uncertainties in the performance of manufactured parts compared to their design specifications. These uncertainties could lead to products not complying with some requirements, resulting in possible failure and accompanied maintenance. A more stable design can be obtained by focussing on the robustness of the design, while taking into account tolerances related to the material properties, manufacturing processes, testing and operational conditions. Introducing probabilistics, deviations from nominal design can be quantified probabilistically, which can then be used as a feedback loop to improve the robustness of the design. In this section a methodology is proposed for improving the robustness of wind turbine designs, involving:

- A probabilistic methodology to include sensitive design, testing and manufacturing parameters
- Automatic (parametric) modelling to automate model building for the probabilistic methodology

The proposed methodology is presented in the form of a flow chart in Figure 2-3, where the embedded classical design process is shown in grey.

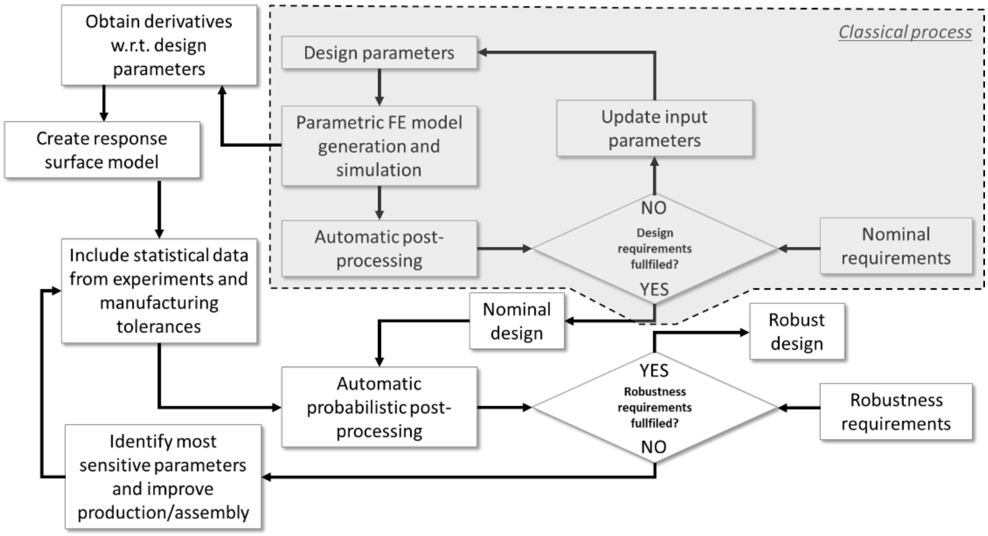

Figure 2-3 Robust design flow diagram

The robust design approach is based on numerical FE simulations including the design parameters. In this case a parametric FE model is used, allowing for automatic FE model generation. This is important because the FE model will be used in a series of sensitivity studies, resulting in the derivatives of the model response with respect to the design parameters. Since this involves many simulations, automation is considered a necessity.

The obtained derivatives are used to obtain a response surface of the model with the design variables as degrees of freedom. The response surface model is combined with statistical data from experiments and manufacturing tolerances to obtain the probabilistic model. This model provides the response of the design and the probabilistic distribution. The standard deviation of the distribution is considered a measure for robustness. A more detailed description of the probabilistic model is shown in Figure 2-4. Here the response surface is excited by a random generator selecting configurations based on statistical data and manufacturing tolerances to obtain a distribution to the nominal response.

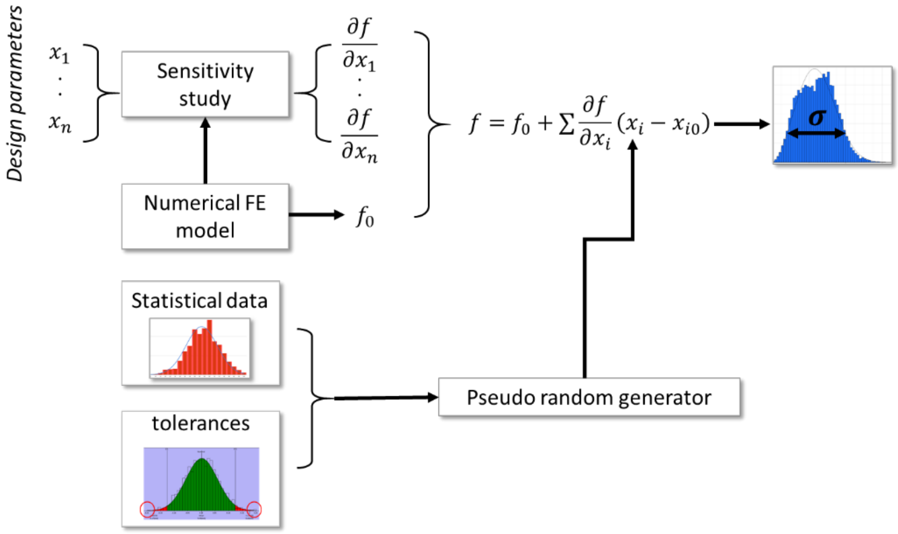

Figure 2-4 Probabilistic model

This model provides a probability distribution of the response of the design and the sensitivities of the design parameters. This information can be used to improve the robustness of the design, by addressing the most sensitive parameters. Examples of improvement measures are; performing more experiments to reduce standard deviations in experimental results or tightening manufacturing tolerances.

2.3 Design optimisation

In designing the blade of the future, design optimisation will provide further opportunities to extend the current limits of blade design and improve the efficiency of blades, thereby reducing the overall LCoE. Four opportunities for optimisation are recognised: structural (topology) optimisation, aero-structural optimisation, optimisation for robustness and optimisation for segmented blades.

Structural optimisation
Although most of the performance of wind turbine blades is determined by the aeroelastic behaviour, purely structural optimizations may also prove to be useful for certain sections of the wind turbine blade. For example, the design of the root section of the blade is entirely driven by its structural response. Besides, this section is challenging to design, as it has to transfer the loads from the blade to the hub and connect the circular cross sections to the rest of the blade. Rao [5] has found that bending stresses can be introduced on the T-bolts that connect the blade to the hub, which is detrimental for the performance. Using a structural optimization procedure the root section is redesigned to introduce less bending stresses on the T-bolts while reducing the mass of the root section. Impact of alternative connection methods are facilitated by effective structural optimization.
A free-form design optimization procedure such as topology optimization would be particularly suited to design a root section, but manufacturing constraints need to be taken into account.

Aero-structural optimisation
As introduced in Section 2.1, the aeroelastic deformations of the blade can be tailored such that it results in favourable aerodynamic and structural performance

by exploiting the inherent coupling between bending and twisting of the wind turbine blade. This is called aeroelastic tailoring and can broadly be induced in two ways: through geometry (e.g. curved or swept blades) or through the anisotropic properties of composite materials (i.e. extension-shear or bend-twist behaviour induced by off-axis plies).

Aeroelastic tailoring has its origins in aircraft propellers and aircraft wings, but has also attracted the attention of the wind energy sector. In the past decade, several studies have been performed and analysis and optimisation tools have been developed with the goal of optimising the aeroelastic behaviour of slender wind turbine blades to reduce the LCoE while preventing unwanted behaviour like flutter.

As part of the EU FP7 Project INNWIND, several studies have been performed on the DTU 10MW Reference Wind Turbine (RWT). At DTU, the aero-structural design tool HAWTOPT2 ([6], [7], [8]) was developed and applied to maximize the Annual Energy Production (AEP), while maintaining the platform design loads such that the optimised blade can still be installed on the existing platform. The optimised blade showed an increase in AEP of 8.7% with respect to the baseline design by modifying chord, twist, the location of the internal structure and the thickness distribution. The extreme and lifetime equivalent loads were maintained within 5% of the baseline design except for the root torsion fatigue loads that increased by 15%.

Within the same project, Bottasso and co-workers ([9], [10], [11]) developed the multi-disciplinary research code Cp-Max (Code for Performance Maximisation) at the Politecnico di Milano and the Technische Universität München. The code consists of a Cost of Energy (CoE) evaluation and a separate aerodynamic optimisation to maximize Annual Energy Production (AEP) and structural thickness optimisation to minimize the Initial Capital Cost (ICC) under frozen aerodynamic loads. These are then combined in an outer loop to minimize the overall Cost of Energy. Initial applications to the DTU 10MW RWT indicated a potential CoE reduction of 7.0% because of a higher AEP despite higher ICC.

Finally, within INNWIND, Manolas et al. [12] focused on the combined application of passive load alleviation through tailoring the bend-twist coupling and active load alleviation through individual pitch control and individual flap control. The bend-twist coupling was tailored by rotating the spar cap UD material ply angle and introducing blade sweep. Initial results show potential for load alleviation, but depending on the applied combination of load alleviation methods, increased tower fatigue loads were observed, while reducing blade fatigue loads, indicating the need for further investigations.

More recently, the University of Bristol has started developing Aeroelastic Turbine Optimisation Methods (ATOM) with the goal of directly optimising for LCoE. ([13], [14], [15], [16], [17], [18], [19]) Currently, an iterative “frozen-loads” approach is applied, where twist angles are first optimised for maximum AEP after which load envelopes are computed from design load cases (DLCs) and the structure is optimised. Work is ongoing to apply this to the integrated aero-structural optimisation of wind turbines.

In conclusion, by exploiting the inherent bend-twist coupling of wind turbine blades and optimising the directional stiffness of the blade, the structural design of the next generation of wind turbine blades could be further improved. Although various aspects of aeroelastic tailoring and aeroelastic optimisation applied to wind turbine blades have been investigated, an integral approach that investigates the complete aero-structural design space appears to still be missing. When looking at the structural design, for example, optimisation has been limited to varying the thickness, while keeping the stacking sequence constant. Further improvements could be found by, for example, applying knowledge from the aerospace sector on aeroelastic optimisation of tow-steered composite wings. [20] The main challenge will be making a trade-off between, on the one hand, the increased CAPEX because of the increased complexity of the design and, on the other hand, the possibility of increased blade length through load alleviation and blade mass reduction.

An integral design approach can also include topology optimisation to further reduce the weight of the turbine blade. Wang et al. [21] demonstrated an integrated aeroelastic shape optimisation and structural topology optimisation, as illustrated in Figure 2-5. However, in this work, isotropic material properties were used.

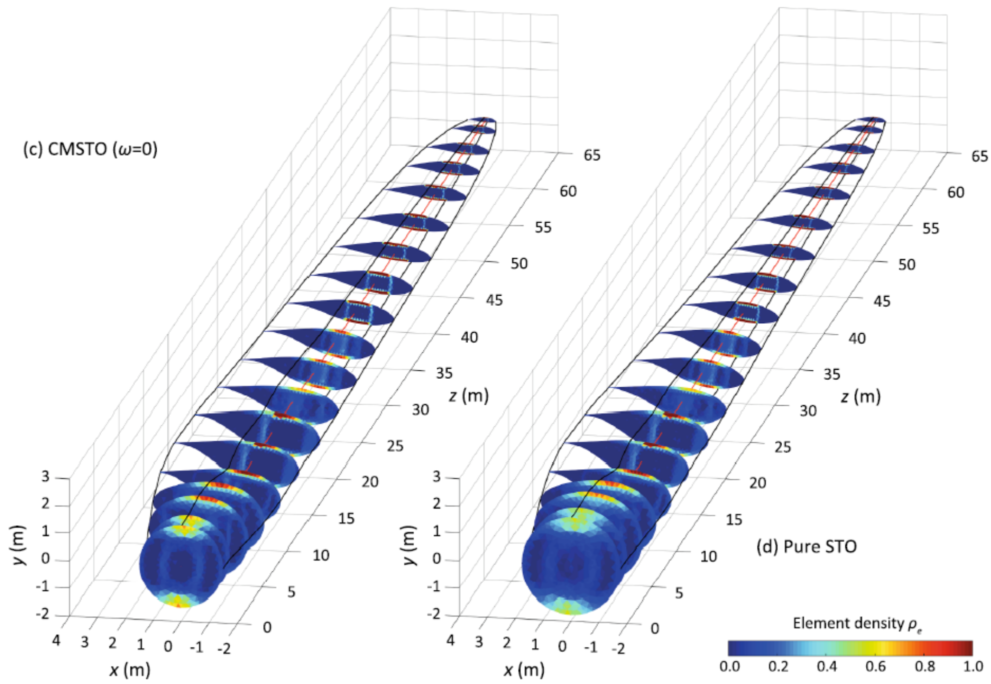

Figure 2-5 Integrated aeroelastic shape optimization and structural topology optimization

In addition, an integral design approach could consider degradation of the turbine blade. Therefore, the aeroelastic design should be robust to this increase in surface roughness, as was also proposed by Ehrmann et al. [22] and Puraca et al. [23]. To determine the expected roughness accumulation over the years, an experimental approach may be taken where a 3D scan of the surface is made. Alternatively, cheap computational models may be created that can compute for instance the accumulation of insects on the surface [23]. The corresponding spread in roughness over the life span may then be included in an probabilistic aeroelastic optimisation to generate blade designs that are robust to variations in the surface roughness.

Optimisation for robustness
The robustness of the blade design towards other parameters is also an important step towards the reduction of maintenance costs. A robust computational design procedure for blades including probabilistic computations does not only reduce the chances of failure, but more importantly it also increases the degree of certainty with which the performance can be assessed. As such, more accurate maintenance cycles may be used, avoiding unnecessary costs. Zheng et al. [24] present a robust shape optimisation of the first eigenfrequency of a wind turbine blade. A robust design approach should include a distribution for all the parameters in which a spread can occur, such as the material properties and the manufacturing tolerances, as described in Section 2.2. These parameters are not always consistent because blades may be manufactured locally in different locations across the world, in different factories and in different climates.

Optimisation of segmented blades
Another design aspect to consider is the trend towards segmented blades [4], leading to several opportunities for optimisation. One possibility is to design a general root section that can be applied to several different blade designs. Furthermore, a staggered optimisation procedure may be defined, where an aeroelastic optimization is employed to determine the best locations to join blade sections, and a purely structural (topology) optimisation may be used to design the connections itself.

3 From manufacturing to decommissioning

3.1 Automation in production

Wind turbine blades are the largest series produced products in the world. A typical 5GW wind farm with 27MW turbines in 2040 will require ~550 wind turbine blades. Given the fact that blade designs will become more and more critical, it seems a logical step to look for a more automated process to produce future wind turbine blades even more reliably. Manual labour will be replaced by the repetitive quality, tirelessness and potential cost saving of robots. However, the extent to which automation is applied, really depends on the design of the blade of the future. Will it be an incrementally improved product, based on today's design? Or will it be a radically changed design, based on the available production methods and materials?

Wind turbine blades typically consist of longitudinal stiffening girders, named spar caps, connected by shear webs. The spar caps connect to the root through a transition laminate that guides the loads to the circular root section, which in turn is connected to the bearing in the hub with studs/bolts. The aerodynamically efficient shape is formed by sandwich panels (outboard) that have the spar caps integrated. Around the perimeter, the shells are glued. Likewise the shear webs are glued to the spar caps. Many of the production methods applied are based on manual labour: placing dry glass fibres or carbon rods in a mould, applying aiding materials, followed by vacuum bagging. The infusion of the laminate, as well as the curing is supported by an automated process already. Are there other opportunities for automation?

It is important to note that automation is not a goal by itself [25]. It must be based on an optimisation target. Blade manufacturing can be split up in different phases. Each phase has its own challenges and potential optimisation opportunity. But not every task within those phases lends itself easily to be automated. Moreover, humans are incredibly versatile and inventive to deal with unexpected changes in plans. Based on current manufacturing methods, it will be hard to beat a human in terms of quality & speed. That is why we see limited levels of automation in the current production processes.
When we design for automation, or when we assume certain production methods to be available in 2040, we can look differently at the options for our 145m blade.

3.2 Mould manufacturing

Traditionally, moulds are manufactured off of positive plugs. Plug manufacturing is already automated to a large extend: a base is milled out of foam, covered with a laminate, after which a specific paste is applied with the same gantry head that milled the foam. Once hardened, the paste is milled to the final dimension by the gantry milling machine. Once the plug is checked for vacuum tightness, the mould can be manufactured, with quite similar techniques to the blade that will later be produced with that mould. For rapid prototyping, one could consider direct moulding, effectively omitting the plug manufacturing process [26]. Also steps are being taken by OEMs to print the sand mould for large castings [27]. Efforts are being made to create flexible moulds that could produce different shapes of products [28].

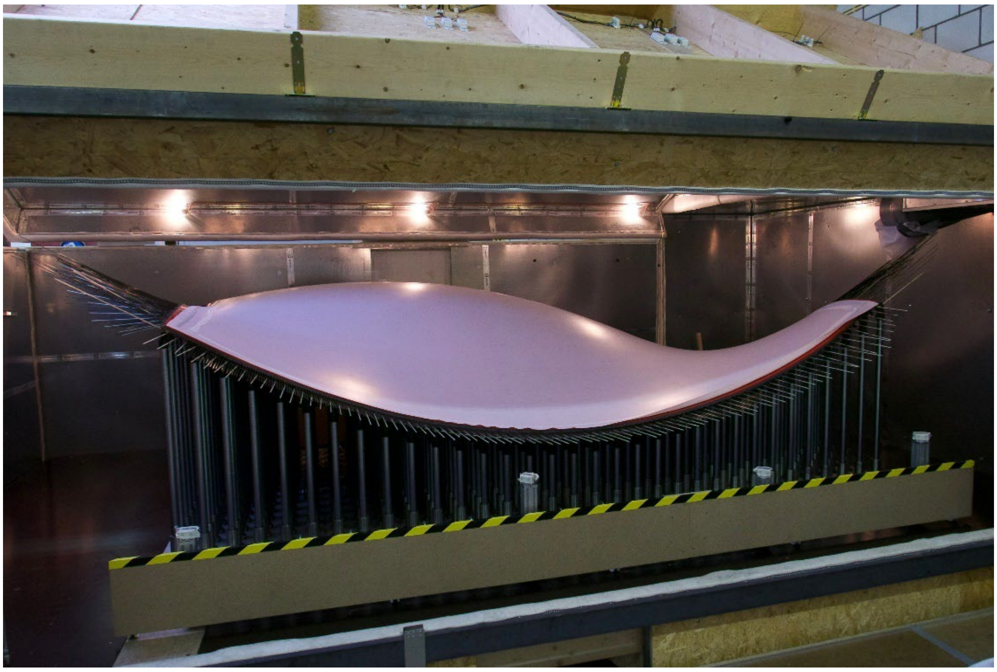

Figure 3-1 Flexible moulds can reduce waste (source: https://nl.linkedin.com/company/curve-works)

3.3 Automated kitting (CAD to 3D milling)

In the near future, all blades will be designed with recyclability in mind. We will see a transition to thermoplastic core materials, bio-based resins (or Liquid Crystalline Polymers (LCP's) or vitrimers) and perhaps even bio-based or more environmentally friendly fibres. Whatever the makeup of the final product will be, the production process starts with material preparation. Kits are made for each blade, so that materials can be tracked from the moment they come into the factory until they are processed into a blade with a certain serial number. The process of preparing the material is called kitting. Kits are then linked to a certain product, i.e. a spar cap, a shear web, a shell, a root ring or a balancing tray. Fibres are often processed in rolls, especially in the main mould. Nesting is used for smaller sections of raw materials to reduce waste. Automated cutting tables are an option both for dry fibre stacks and for pre-pregs, if applicable. Moreover, the kits for the sandwich panels are a complex combination of full panels, combined with tapered sections. All require wedges around the perimeter to guide the stitched fibre stacks that will form the faces of the sandwich panels. 3D CAD modelling is already used and 3D milling by an automated milling station can reduce waste, reduce cycle times and improve quality over manual processing of core materials. Taking it a step further, an overhead robot could place the core-puzzle into the main mould, providing consistent quality and placement accuracy.

3.4 3D printing and tape laying

With the promise of a topologically optimised design and the availability of printers that can print continuous fibre reinforced thermoplastic or liquid crystalline polymers in high enough volumes, 3D printing components for blades could become interesting [29].

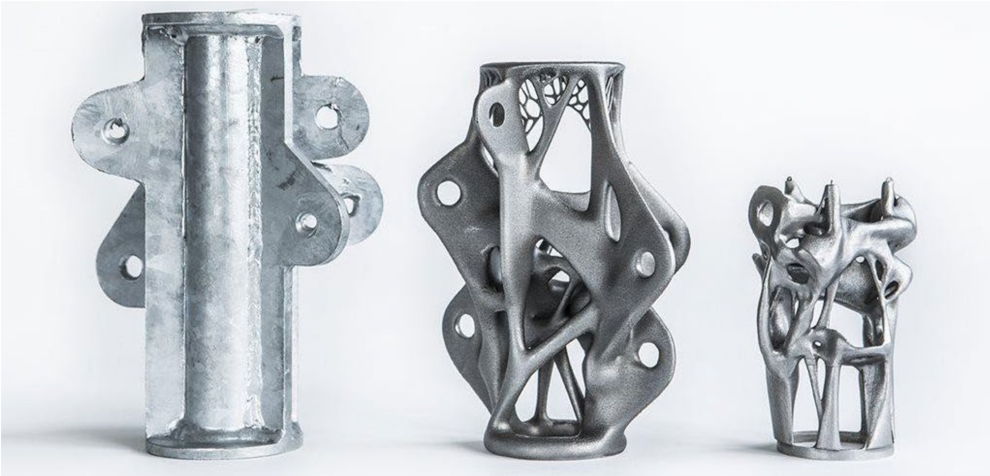

Figure 3-2 Traditional (left) versus topology optimized printed structures (middle, right) (source: https://www.protocam.com/learningcenter/blog/generative-design/)

Again, it is important to determine whether a switch towards printing components or sections would make sense. The optimisation target should justify such a decision. An intermediate step could be fibre placement, or rather tape laying of laminate on a mould. Typically tape laying is a very capital intensive production method to set up. The resulting product shows high accuracy in fibre direction, but a tape laying robot often spends more time on producing a part than a human would on the same mould. Tape laying for a main mould would become interesting once the boundaries of accuracy or quality are reached for a given blade design. A robust design for a product involving manual labour will look differently from a robust design developed for a high level of automated production.
In 2040, we could imagine an optimised design for a shear web, resulting in a lattice structure which is tape laid on a flat table mould by a tracked robot. Perhaps structurally vulnerable sections of the blade are tape laid with prepreg material in the main mould as well, then subsequently co-infused with a dry fibre stack positioned by hand. A hybrid form would make most sense from a cost and cycle time perspective. Ultimately, topology optimisation together with liquid crystalline polymers (LCP) open the way to 3D printing an internal bone-like shear structure, rather than the traditional shear webs (also see Chapter 6).

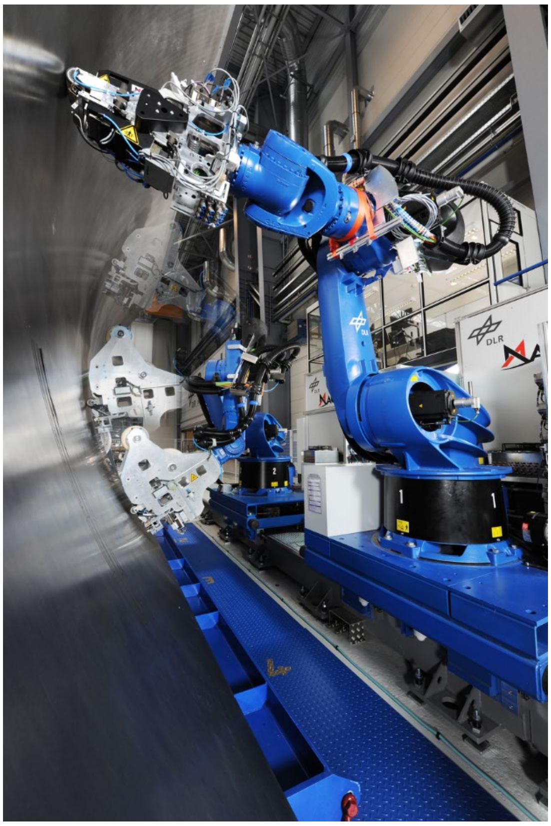

Figure 3-3 Automated tape laying (source: https://www.researchgate.net/figure/GroFi-realizing-a-combined-usage-of-ber-placement-and-tape-laying-technology_fig3_297753319)

3.5 Bonding over large lengths

Bonded joints are common in wind turbine blades. The shear webs are often adhesively bonded to the spar caps, the shells are bonded to each other as well. The bond line is therefore a complex load bearing part of wind turbine blades. Traditionally, glue was applied by hand. Nowadays, automated mixing of component A and B is done (if required) after which the (mixing) machine will pump the glue to a specially shaped nozzle. The nozzle is shaped specifically to deposit the right amount of glue for that given location and bond thickness design. Up until recently, this application process was done by hand. A worker would position the nozzle and work his or her way down the leading and trailing edge of the blade, as well as the tops of the shear webs. Not only did that create variation in glue quantity from blade to blade, it could also lead to air inclusions in the bond line. A transition to automated glue deposition is taking place with robots applying the glue hanging from a gantry crane. This drastically reduces the application time and improves the consistency in a repeatable way. This not only improves the reliability of the end product (lower variance and quality uncertainty), it reduces rework and in the long run can omit certain quality checks in the end product.
Alternatively, when the matrix of the future blades will be a thermoplastic material rather than a thermoset, vitrimer or LCP, welding of components becomes an option. There are different ways to fuse two thermoplastic parts together [30]: resistance welding using a foreign material to heat up the weld area, or induction welding using the presence of carbon fibres in the components itself to melt the surrounding thermoplastic. Both methods require external pressure to prevent air inclusions and sufficiently high bonding quality.

Figure 3-4 Gantry robot example for laser cutting (source: https://www.kuka.com/en-de/products/robot-systems/laser-cutting-gantry)

3.6 Machining the rough product

Before bushings were integrated in the root of a blade, the root of the blade would consist of a monolithic laminate of up to 100mm thick glass/epoxy or glass/polyester. A milling machine would then need to machine the root to give the right length a correct flatness. Subsequently holes would be drilled for the IKEA-style root nuts (T-bolt connection). Nowadays, root bushings are co-infused and root-plates are used in the mould to reduce the amount of finishing work that needs to be done on the final product. [31]

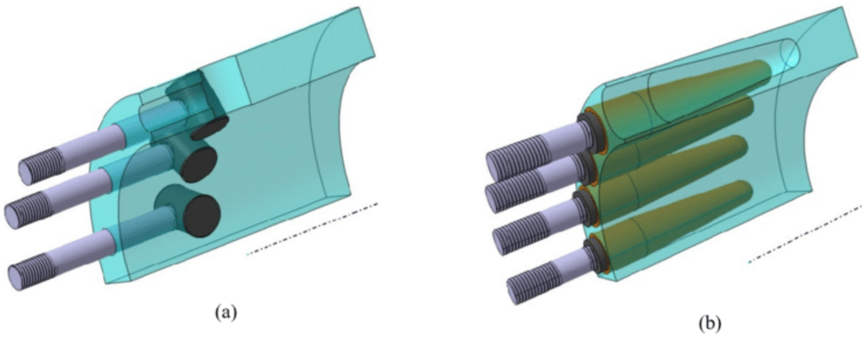

Figure 3-5 The T-bolt (IKEA) connection (left) and the Rootbushing connection (right) [32].

However, the rest of the blade still requires significant finishing. Often material extends onto the flanges of the mould to facilitate the infusion process. This so-called flash needs to be removed from the blade after the glue-up and release from the mould. A track guided robot with laser guided relevant distance information could grind (or water jet cut) this flash automatically, followed by a sanding robot to ensure the correct airfoil shape at the leading edge and trailing edge.

3.7 Finishing the surface

The surface finishing of a wind turbine blade requires sanding, pore filling, top coating and application of leading edge protection. The industry has moved a long way from manual sanding, to orbital sanders to large surface sanders. The surface area of a LM107 can be estimated to be ~700m^2. Sanding such a large surface consistently is a challenge, let alone the safety aspects of working at height and the dust that is created, despite the dust evacuation equipment. For a 145m blade, the surface area will be over 1150m^2 per blade. In 2040, this work can best be done by a small army of tracked robots equipped with 3D CAD info, local laser sensing and a pressure limited sanding head.
Once the blade is sanded, it requires cleaning before a pore filler is applied. Both automated cleaning and automated application of pore filler can prevent waste and reduce the amount of volatile particles in the production environment. A second automated sanding and cleaning step prepares the blade for coating.
The quality of the top coat of a wind turbine blade is extremely important in terms of operational costs. The coat should be applied evenly, with the correct surface roughness. Wear and tear on the blade, caused by particles in the air, dirt and rain can easily erode the paint layer and reduce the thickness. This is especially the case at the leading edge of the blade, at the outboard section. The tip of a wind turbine blade reaches speeds in excess of 90m/s or 325km/h. Normal top coat is not enough for this part of the leading edge, as rain and hail can hit like stones, quickly eroding the surface and leading to reduced aerodynamic efficiency. And aerodynamic efficiency is especially important in the outer 30% of the blade.
Leading edge protection is applied at the locations where local airspeeds are expected to lead to erosion. This can be applied in the form of a tape or a tough coating system. Both the topcoat quality and leading edge protection could benefit from automated application [33], [34]. This station could also be used to perform ultrasonic scans of the whole blade.

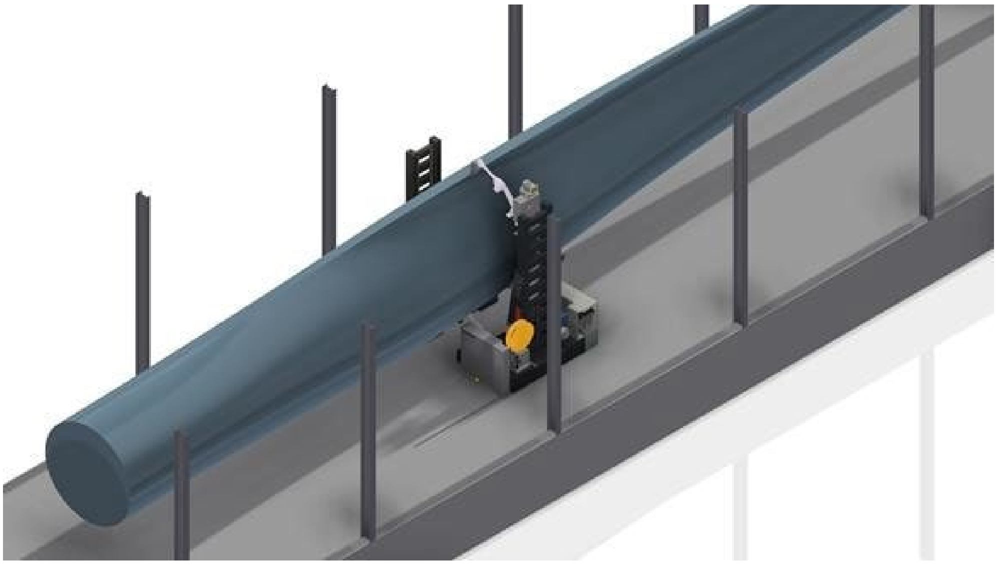

Figure 3-6 Automated blade coating (source: https://www.qlayers.com/bl8robot.html)

3.8 Quality control

Adequate monitoring of the quality of the end product happens throughout the production and life cycle of the wind turbine blade. From incoming goods control, to visual inspection when applying materials in the mould, to mixing ratios, to curing temperatures, design parameters, defects and stresses under loading. All these quality checks provide information on the status of the product at every stage of its life. For large blades opportunities for automation of quality control lie amongst others in monitoring the lay-up, scanning for defects through thick composite structures, scanning the aerodynamic shape under gravitational loading only, and applying in-blade sensors in combination with a predictive twin of the rotor. Combined with all information gathered during the production process, this data (with its associated uncertainty) gives insight into the likely expected lifetime of every blade that rolls of the production line. Automation can help reduce the uncertainty in the data and increase the amount of information available of the whole structure, while keeping the quality control time equal or even reduce it.

3.9 Handling

Transporting massive structures without damaging them or causing unsafe situations can be challenging. Synchronising the overhead cranes and releasing a flexible 145m blade from a mould in a single piece is a feat by itself. The blade requires repositioning several times after that to facilitate access for machining, quality checks and finishing. Safety could be further improved if an automated system scans for human activity around the blade when it is moving or due to move. Magnetic tracks in the floor can help to determine where a stationary released blade is allowed to be on the factory floor and thus help manage potentially danger zones and safe zones. The bogeys supporting the blade are then guided by these tracks inside and outside the factory. Specially designed grippers will lift the blade directly onto a vessel which minimizes the handling and loading of the blades. Automation can thus help reduce the risk of damage. The bogeys and grippers themselves should be smart as well, measuring clamping pressure, weight distribution, etc, warning the operator when these are expected to go outside the programmed bounds. Also here, measured information can be added to the data-library of the specific blade further specifying its expected lifetime.

Figure 3-7 Blade handling exerts non-conventional loads on blades (source: https://www.ge.com/news/reports/extreme-measures-107-meters-worlds-largest-wind-turbine-blade-longer-football-field-heres-looks-like)

3.10 Installation & decommissioning

Remarkably, some of the most limiting loads on a blade take place during handling, transport and installation. Special tools are developed to minimize these loads and prevent additional design requirements for load cases that normally do not occur during the operational phase of the blade. Measuring actual loads on the blades during installation will help assess the effect on remaining life. If installation loads become of an order of magnitude where they define the blade design to a greater extent, segmented blades could be considered, with all their pro's and con's (see Section 2.1).

Figure 3-8 Two-crane SG14-222dd blade installation (source: still from https://www.youtube.com/watch?v=zoAOlrdT46g)

The first wind farms, installed in 2005 and earlier are currently reaching end of life. With expensive installation vessels planned to reverse-install wind farms, there are opportunities for optimization both for disassembly as well as logistics towards the ports and processing factories. Depending on the level of re-use intended for the blades, partial processing or even full processing can be considered offshore. For future blades, the matrix is most going to be a heat-recyclable material, impacting the way of processing both offshore as well as on the quay side. Such a bulk process could take advantage from automation, increasing the predictability and safety of handling such large structures, while optimizing for properties of the processed materials.

4 Testing

Wind turbine blades require a type test for certification. Blade testing is governed by the IEC 61400-23 guideline[1], which states: “The purpose of the testing activities is to confirm to an acceptable level of probability that the whole population of a blade type fulfils the design assumptions”. A typical blade certification test programme is built up from the following components:

- Determining blade mass and centre of gravity
- Modal test
- Quasi-static test
- Fatigue test
- Quasi-static test

These full-scale tests are very expensive, time consuming and, for the largest offshore wind turbine blades, only a limited number of institutes can perform them. With the increasing length of wind turbine blades, these challenges become even more prominent. In order to address these challenges, three main solutions are proposed and are currently being investigated: multi-axial testing, segmented blade testing, and virtual testing.

Multi-axis fatigue test methods have been investigated by a Danish consortium led by DTU within the Blatigue project. ([35], [36], [37]) Multi-axis fatigue test methods have two advantages compared to separate flap and edgewise tests: (i) the test loads better match the loads to which the blades are exposed to in real operational conditions and (ii) the overall test time is shortened, since flat and edgewise loads can be tested simultaneously. This project is currently being followed by the Blatigue2 project, which will further improve multi-axial fatigue test methods and attempt to reduce the fatigue test time of large blades through testing blade segments. [38]

Fraunhofer IWES [39] is also constantly working on implementing and improving these test methods. Ha et al. [40] present a segment test optimisation methodology that showed a potential fatigue test time reduction of 43% for a 60m blade and 52% for a 90m blade.

However, to really accelerate the design and certification process of wind turbine blades and reduce development cost, virtual testing could be of great value. Validated simulations are used to reduce large-scale tests and eliminate full-scale tests. The keyword is the word *validated*, meaning the applied simulation methodology is validated by experimental tests and its accuracy is quantified prior to its use. The building-block validation approach, depicted in Figure 4-1, is used for the validation process. First, material tests are performed on the bottom layer, as input to the model. Next, joints and assembly aspects are tested and used to calibrate and validate the numerical counterparts of the experiments. In the next block, critical structural sections (e.g. areas with high stress concentrations or critical segments) are tested and used for validation.

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[1] IEC-61400/23 Full-scale structural testing of rotor blades, June 2014 (a maintenance team is currently working on a revision of this document)

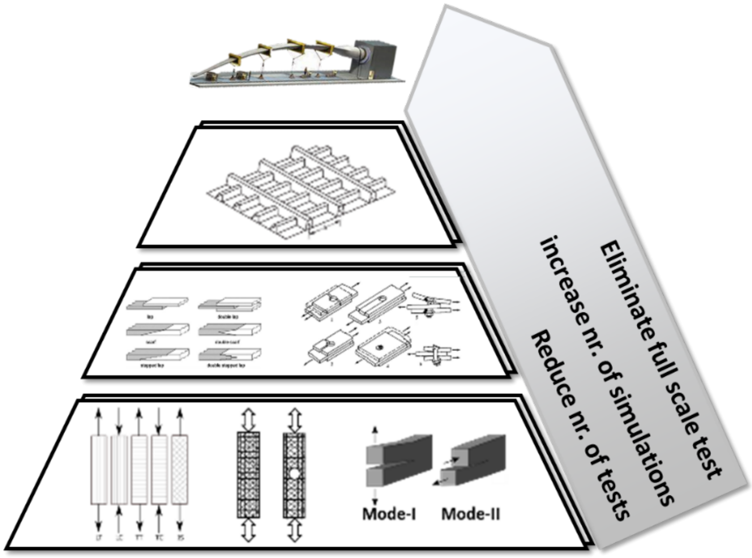


Figure 4-1 Building-block validation pyramid

The accuracy of the numerical model can be assessed by including all uncertainties in the numerical model and in the experimental results. This provides a quantitative accuracy of the model, defined as the "*predictive capability*" of the model.

The ever increasing size of wind turbine blades calls for an increase in scale for test facilities, which could become a limiting factor for certification. Validated simulation models can be used to identify critical parts and the accompanied stress-state and failure modes in a certification test setup. This information can then be used to define a segmented experimental program that results in a comparable stress-state and will induce identical failure modes to the full-scale test without the need for this full-scale test. This process is depicted in Figure 4-2.

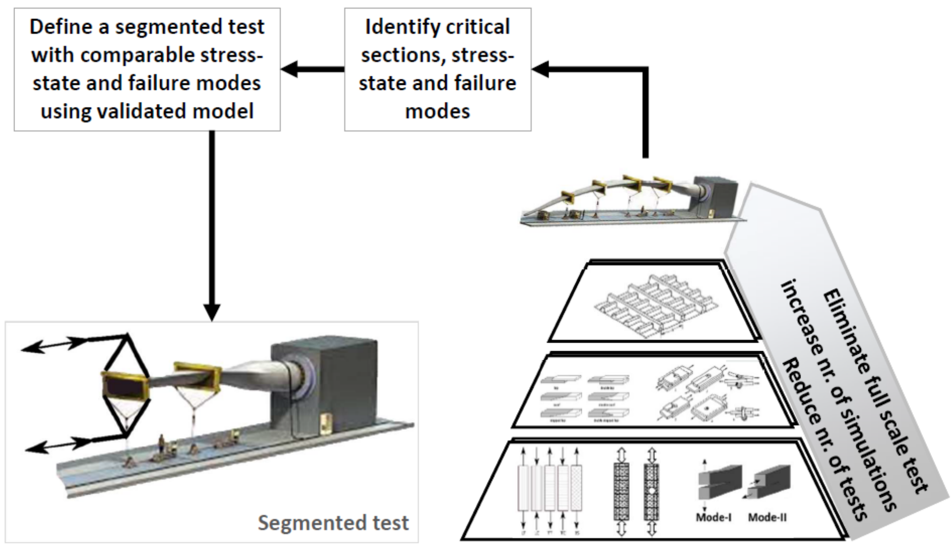


Figure 4-2 Using building-block validation approach to define segmented experiment

5 Operation & maintenance

One of the most important trends in operation and maintenance of wind turbine blades is the rise of structural health monitoring and digital twins. Although it is possible to retrofit existing blades with these technologies, incorporating these technologies in the design process of the blade of the future provides additional opportunities.

For example, during the design phase, the sensor location can be optimized based on the locations that are the most sensitive to variations and damage. To this end, the robust design framework proposed in Section 2.2 can be used. These sensors can then be embedded in the composite material during manufacturing. Furthermore, incorporating a structural health monitoring system in the design of wind turbine blades allows for less conservative maintenance cycles, since damage may be detected early or even prevented by the SHM system. Moreover, the actual structural loads collected by the sensors can be combined with information such as local weather data and energy prize information, which can be fed into the controller for optimised operation for various target settings.

With respect to digital twins, the Danish-German JIP ReliaBlade aims at developing and demonstrating techniques to create a unique digital twin for each individual wind turbine blade with its specific defects and imperfections. The digital twin can track not only the current state of the blade but also predict the future state - as damages initiate and grow through its entire life cycle [41]. Figure 5-1 shows an overview of the project.

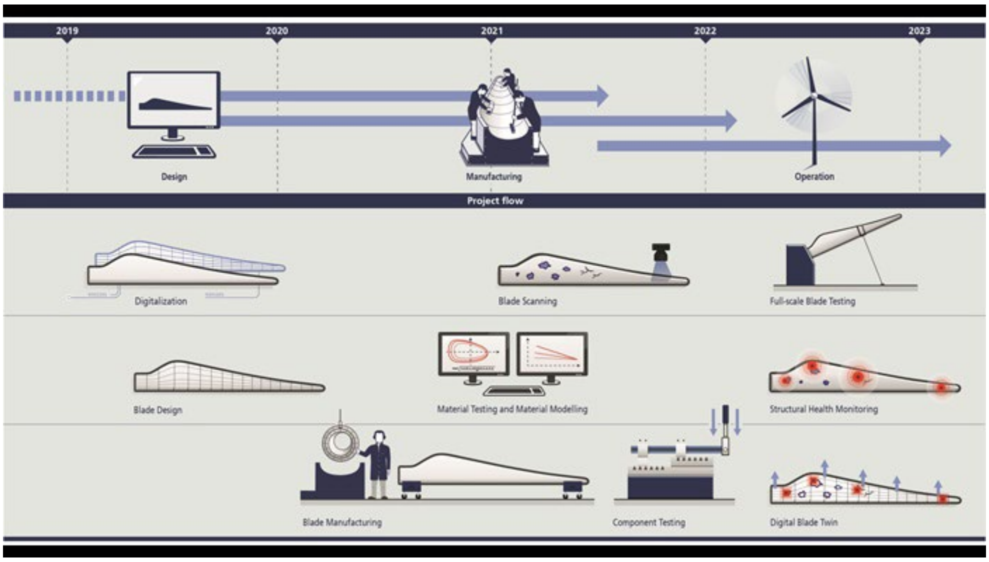


Figure 5-1 – Reliablade project overview (Source: https://www.reliablade.com/about)

6 Recycling

With the rapid growth of wind energy, the amount of waste resulting from decommissioned wind farms will rapidly grow as well. The common assumption is that 1MW of installed power equals a mass of 10 tonnes (10.000 kg) of wind turbine blade waste at the end-of life. For 2019, this meant an estimated 121.490 tonnes of waste. [42] The University of Strathclyde (Scotland) predicts, based on their research, an increase of 400.000 tonnes per annum in 2030 towards two million tonnes by 2050.

When lifetime-extension after operating permit extension (from 20 to 30 or even 40 years) or after retrofitting, has reached its limits the wind turbines will need to be dismantled. Currently contractors in various countries often still store the blades or dump them as landfill until cost-effective recycling options become available or landfill is no longer an attractive alternative. OEMs, such as LM Windpower (GE), Vestas and Siemens Gamesa are therefore exploring the development of recyclable blades [43], [44], [45], [46].
Different recycling routes can be followed for the wind turbine blades. Below, Figure 6-1 shows an overview of the options for recycling and recovery of glass-fibre and carbon reinforced polymers (GFRP and CFRP) as given by Sommer and Walther. [47]. The current generation of blades is still mostly reinforced with glass fibre, but the use of carbon fibre is expected to increase due to the increasing blade sizes and loads. This is related to the higher performance (especially the higher strength and stiffness over density ratio) of carbon fibre over glass fibre. The same holds for the resins used that tend to shift from polyester and vinylester to epoxies for the higher loaded parts.

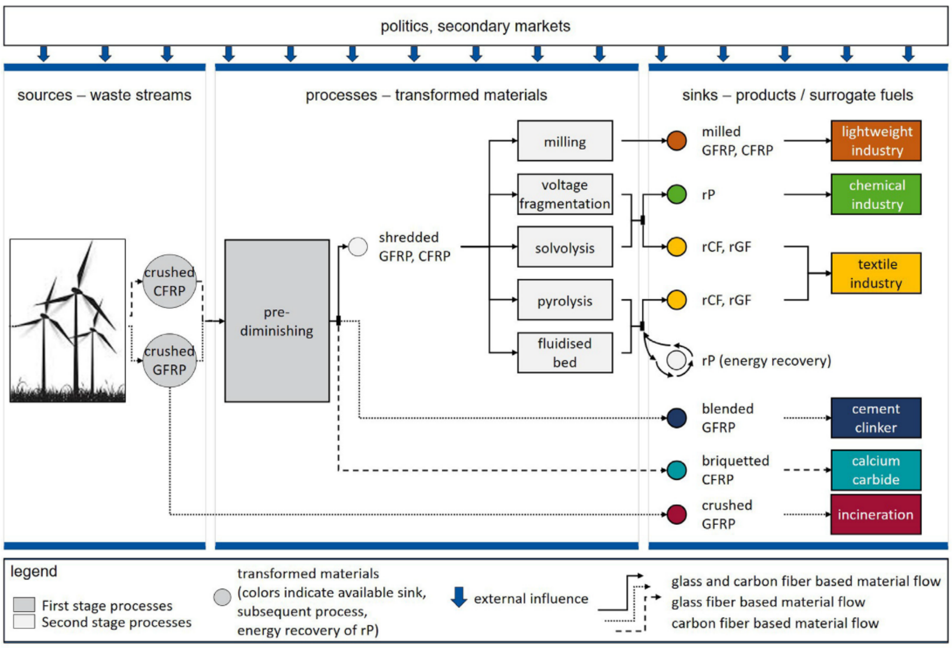


Figure 6-1 Recycling and recovery options for GFRP and CFRP for wind turbine rotor blades. [47]

6.1 Recycling options

The selected material also impacts the recycling routes, which in summary are: shredding, pyrolysis, solvolysis, upgrading glass fibre, and reuse of the blade for structural purposes.

Shredding
The blades are reduced in size by mechanical processing (shredded, cut and ground to small particles) and reused in a different form as a filler or as a reinforcement in concrete, reinforced plastics or other products. In this case it is estimated that about 80% recycling/downcycling is achieved due to material losses in the processing [42]. Much of the thermoset composite products are nowadays processed in this way. However, there seems to be little demand for the regained materials (grinded resin powder, short fibres, aggregates, fibre reinforced shards) and materials are not reused in the manufacturing of new blades.

Pyrolysis
Using pyrolysis polymers can be 'cracked' at high temperature (450-700 °C) in a chamber with a limited amount of oxygen, reducing the polymers to fibres, oils and gasses. At high temperatures, the strength of the glass fibers reduces, which has consequences for the possible application of the recovered fibres, while carbon fibers are less sensitive to degradation. The required heat and the reuse of the recovered materials (oils, gasses, fillers and fibres) can result in a feasible solution for carbon fibre recycling [48]. Recent research by TNO with Brightlands Materials Center has shown that using low-temperature pyrolysis an acceptable quality of recovered glass fibre can be used in recyclable injection moulded products [49]. To reduce the heating cost, the ‘fluidized-bed’-technology (a microwave technology) is being explored as well, but not yet commercially available. Recently Shell decided to invest in recycling company Bluealp for converting hard-to-recycle plastic in pyrolysis-oil of which durable chemicals can be made [49].

Solvolysis
Solvolysis is a recycling technique in which the composite resin dissolves at lower temperatures [50]. The results at lab scale are promising and sometimes combined with the pyrolysis process. Commercial application has been limited up to now [51], but it is a promising route that allows for regaining the weaves as well as the monomers. The process also prevents the formation of carbonised material that contaminates the fibre surface after pyrolysis and can diminish fibre-matrix bonding.

Upgrading glass fibre
A consortium consisting of Aker Offshore Wind (Lysaker, Norway), Aker Horizons (Norway) and the University of Strathclyde (Scotland) developed a process developed at lab scale by Strathclyde for thermal recovery and post-treatment of glass fibres from GFRP scrap to achieve near-virgin quality glass fibre. Together they work on the scale-up and commercialization of the process. [52]

Reuse of the blade for structural purposes
Full recycling is also possible, if the entire blade can be reused in a second life for structural applications such as buildings, infrastructure or architectural products.

6.2 Design for recycling

Design for recycling is important for new wind turbines in order to make optimal use of the existing and future recycling options in the early development stage. Besides material selection, this also includes the manufacturing and assembly method. The use of specific chemistry, for example, can make the blade more suitable for recycling. Fisher and Lejeail [53] describe a reversible chemistry based on Diels–Alder reactions that are activated by temperature. Washing of the separated fabric using a bio-based solvent acetic acid reclaims fibres with an almost virgin quality and purity. Taynton and Kaffer [54] developed a resin that uses exchangeable imine-linked chemical bonds, called vitrimer. Due to the reversible chemistry the cured materials can be depolymerized and separated from the fibres under mild conditions. The second generation resins can contain recycled resin loadings of 30-40%.

Various core materials are being used in the wind turbine blade industry. Besides traditional core materials such as balsa, PVC, and SAN, the thermoplastic PET is amongst others attractive for its recyclability and the fact that it can be made with recycled content (typically, from waste PET bottles) [55].

From a recycling perspective the use of a single polymer for both fibre and matrix is attractive. The developed single-polymer composites based on polyolefins or polyalkenes, such as polyethylene (Kaypla, Dyneema) and polypropylene (Pure) do offer the recyclability, but are also susceptible for creep. A recent development of a single polymer composite uses liquid crystalline polymers. Liquid crystalline polymers (LCPs) are a special type of thermoplastics with a high degree of crystallinity. At ETH Zurich the self-assembly of liquid crystalline polymer molecules during extrusion resulted in novel material with highly oriented properties. The printed material matched the stiffness and strength of carbon fibre-reinforced polymers. Additional features of the process include recyclability, automated manufacturing and lower carbon footprint. Moreover, the used 3D printing technique allows for production of complex geometries [56], [57].

7 The blade of the future

After having assessed the complete life cycle of the wind turbine blade of the future in the previous sections, we can now sketch a more concise picture. Expecting a 27MW HAWT platform to be the norm in 2040, the blades will have to be around 145m long. Keeping such a giant asset reliable in terms of power generation and maintenance is essential. That will mean the blades need to be **designed robustly**, taking into account all inherent uncertainties of the design, production, testing, and operation to most accurately predict lifetime and obtain reliable maintenance intervals.

The slenderness of very long blades will require a more **aeroelastically tailored** design. By exploiting the inherent bend-twist coupling of wind turbine blades and optimising the directional stiffness of the blade (i.e. aeroelastic tailoring), the structural efficiency of the next generation of wind turbine blades will be further improved. Moreover, the design will aim for **segmented** blades, not only to facilitate transportation, but also to reduce handling and installation loads on the blade itself and the installation equipment. The selection of the location of the joint will be fully optimised.

The blade of the future will be further optimised using an integral approach combining the aeroelastic and structural behaviour requirements with considerations such as life-time, robustness and surface degradation (f.e. LE-erosion). This **integral optimisation** will entail the entire blade design, including segmentation locations and joining techniques. Optimal locations for integrated sensors for structural health monitoring and optimised control are also determined. In turn, this introduces opportunities for a free-form design optimization procedure such as **topology optimisation** used to design the shear load bearing structure of the blade.

Some of the optimisation in design can only be achieved by more **automated manufacturing.** Increasing repetitive quality, 24 hours a day in some part of the production line will reduce room for error and aid manual labour. We foresee traditional production techniques for the shells of the blades, like resin infusion moulding. Sections of the blade that are prone to waviness or wrinkles, like the root, could be produced with **automated tape laying** and/or production on a positive mould. A topology optimized core of the blade leading to a shear structure rather than shear webs will be achieved with **3D LCP printing**.

Finishing of a mass-produced segmented 145m blade will be done in an automated way. Both machining, sanding, coating and handling will be taken over by automated finishing stations on rails and guide loops in the factory floor and in the yard and quay side.

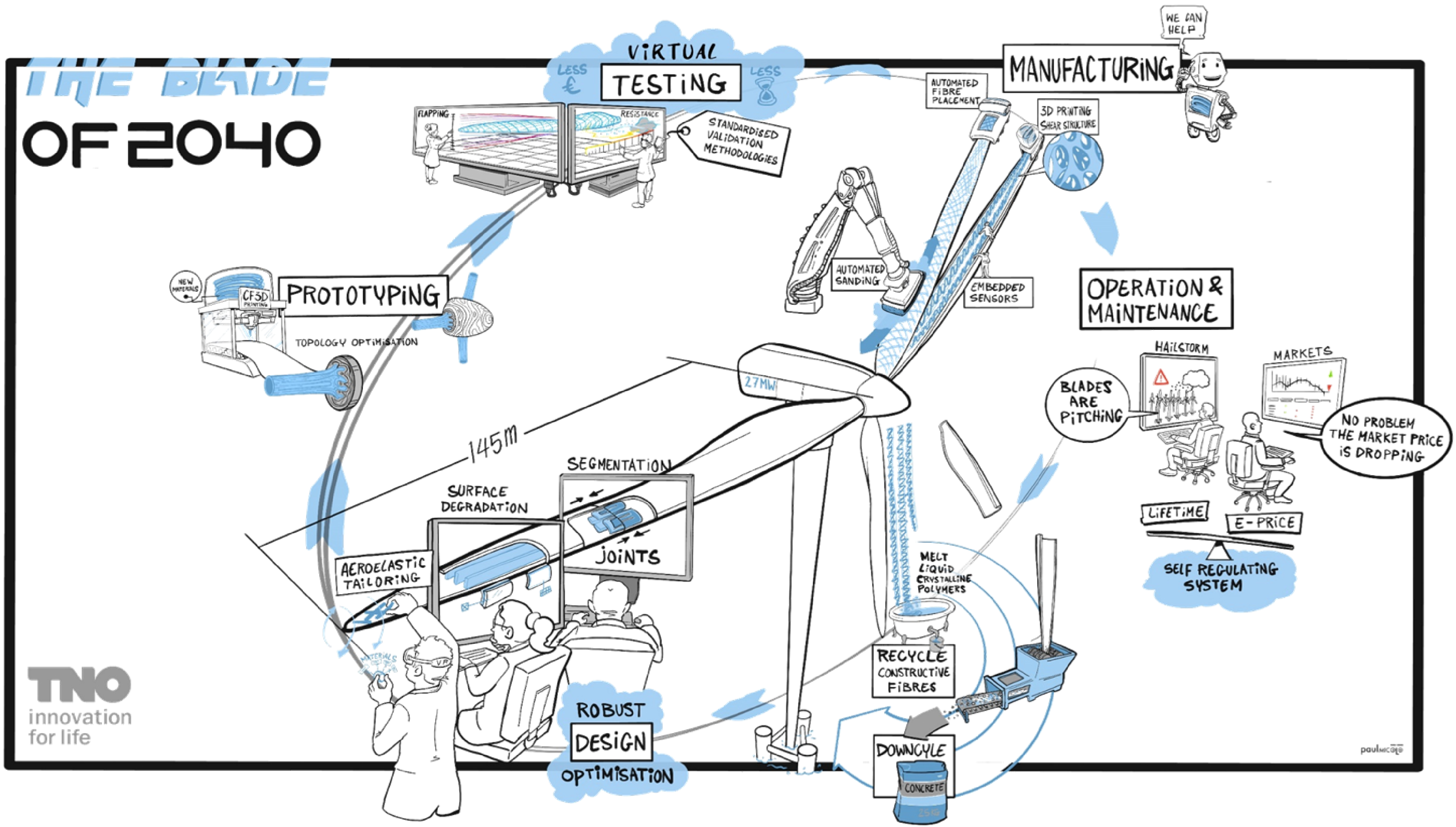
In order to really accelerate the design and certification process of wind turbine blades, reduce development cost, and make the design of blades of the future possible, **virtual testing** will be required. The accuracy of the numerical model can be assessed by including all uncertainties in the numerical model and in the experimental results. This provides a quantitative accuracy of the model, defined as the "*predictive capability*" of the model.

Today's design and qualification process looks a lot different than a few decades ago, as the introduction of computer aided design and manufacturing has changed the way structures are designed and manufactured. In the same manner, the design and qualification process of the future will be radically different than it is today. As the available computing power continues to grow, competition will push companies to rely even more on computer simulations to increase economic efficiency and deliver more robust products. This holds even more so for wind turbine blade manufacturers, where growing blade size also impairs practical limitations forming another motivation to rely more on simulations. It is the confidence in the computing model which will drive the transition to the simulations of the future. **Standardised validation methodologies** will be necessary to objectively quantify the predictive capabilities of numerical simulation models. With certification bodies adopting these methodologies, validated simulations will be used to certify the blade of the future.

Using embedded sensors, the blade of the future will be monitored continuously to ensure **optimal operation and maintenance**. Using actual local weather forecast and energy prize information, digital twin technology will enable the prediction of the future state of the blade as damage grows, allowing for preventive repairs, minimizing downtime of the turbine, while maximising life-time.

A strong emphasis in the design phase is needed to facilitate ease of dismantling at end-of-life and to get **fully reusable materials** introduced in the wind turbine structure. Polymers build with re-mouldable or reversible chemistry are expected to take over the rigid thermoset formulation currently used. While still in the scientific exploration phase also single polymer composites, especially those based on liquid crystalline polymers, will have become a game changer in 2040. At lab scale, 3D printed material already showed material stiffness and strength matching those for carbon fibre-reinforced polymers. In this case both fibre, with highly oriented polymers, and matrix consist of the same base polymer and no separation is needed in recycling.

Combined, these developments will form a truly integrated design approach for the blade of the future.


THE BLADE
OF 2040
VIRTUAL
TESTING
LESS €
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FLAPPING
RESISTANCE
STANDARDISED VALIDATION METHODOLOGIES
WE CAN HELP
MANUFACTURING
AUTOMATED FIBRE PLACEMENT
3D PRINTING SHEAR STRUCTURE
AUTOMATED SANDING
EMBEDDED SENSORS
NEW MATERIALS
CFSD
PROTOTYPING
TOPOLOGY OPTIMISATION
OPERATION & MAINTENANCE
HAILSTORM
MARKETS
BLADES ARE PITCHING
NO PROBLEM THE MARKET PRICE IS DROPPING
LIFETIME
E-PRICE
SELF REGULATING SYSTEM
27MW
145m
SEGMENTATION
SURFACE DEGRADATION
JOINTS
AEROELASTIC TAILORING
MATERIALS
VR
MELT LIQUID CRYSTALLINE POLYMERS
RECYCLE CONSTRUCTIVE FIBRES
DOWNCYLE
CONCRETE
ROBUST
DESIGN
OPTIMISATION
TNO
innovation for life
paulnicolo

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9 Signature

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